FINAL TECHNICAL REPORT FOR GRANT NUMBER: 07-HQGR0084
LABORATORY EXPERIMENTS ON ROCK FRICTION FOCUSED ON UNDERSTANDING EARTHQUAKE MECHANICS

Terry E. Tullis
and
David L. Goldsby
Brown University
Department of Geological Sciences
Providence RI 02912-1846
Tele: (401) 863-3829
FAX: (401) 863-2058
Email: Terry_Tullis@brown.edu
Web Site. http://www.geo.brown.edu/faculty/ttullis/index.html

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TECHNICAL ABSTRACT

In order to determine where best to deploy limited resources for mitigating earthquake loss in the US, we need to understand when and where earthquakes may occur and how intense their accelerations can be. Every time an earthquake occurs, we gain more understanding of the earthquake problem through measurements of ground motion and modeling of seismic sources. In addition to information derived from earthquakes, we can also benefit from improved understanding of the seismic source through laboratory measurements and modeling, to anticipate what may occur in future earthquakes. One of the great gaps in our understanding of source processes is how shear resistance varies on a fault during seismic slip and what this implies about the magnitudes of stress drops and near-fault accelerations. We are helping to fill that gap through our laboratory experiments.

We continue to make significant progress in understanding the gel-weakening phenomenon we discovered, through characterization of the gel on the sliding surface, and identification and characterization of the rock types for which gel weakening can occur.

We have also continued experiments to understand better flash heating/melting. These experiments are conducted at sliding velocities of up to 360 mm/s over displacements too small for gel formation to be significant. Our results, coupled with theoretical estimates of flash temperature, are consistent with flash melting at a sliding speed of 100 mm/s or higher. Constitutive equations for this mechanism are being used in theoretical dynamic rupture models, so it is important that we verify that this mechanism is in fact responsible for the weakening observed in experiments. We now have a high temperature assembly for conducting unconfined experiments on flash heating and gel formation. However, at the highest velocities we can obtain, at which flash weakening appeared to occur with our old room-temperature assembly, we do not see weakening when we use the high-temperature assembly. We are in the process of trying to understand the reason for this difference because at present we cannot be sure which behavior is correct. If experimental artifacts related to the differing stiffness and masses of the two assemblies are responsible for erroneous measurements using one of the assemblies we need to understand them. If flash weakening operates during earthquakes, it would cause large stress drops over very small amounts of slip, and healing would be essentially instantaneous. It is thus important to know whether this mechanism is likely to operate on faults during earthquakes.

INTRODUCTION

This is a final technical report for USGS grant 07-HQGR0084. The grant covers a one-year period, from March 1, 2007 to February 29, 2008. We have continued work to increase our understanding of both gel weakening and flash weakening. The work is relevant to understanding dynamic resistance during earthquakes. We will discuss our progress in detail below.

PUBLICATIONS RESULTING FROM THIS GRANT

Goldsby, D. L., and T. E. Tullis (2007), Flash Heating and Weakening of Crustal Rocks During Coseismic Fault Slip, *Proceedings and Abstracts 2007 SCEC Annual Meeting*, *17*.

Tullis, T. E., et al. (2007), Rheology of fault rocks and their surroundings, in *Tectonic Faults – Agents of Change on a Dynamic Earth*, edited by M. Handy, et al., pp. 183-204, MIT Press, Cambridge, MA.

Tullis, T. E. (2007), Friction of rock at earthquake slip rates, in *Treatise on Geophysics,* G. Schubert (ed.), *v. 4, Earthquake Seismology*, H. Kanamori, (ed.), Chapter 5, p. 131-152, Elsevier Ldt., Oxford.

Beeler, N.M., T.E. Tullis, L.A. Reinen, and A.K. Kronenberg (2007) The instantaneous rate dependence in low temperature laboratory rock friction and rock deformation experiments, *Journal of Geophysical Research*, *112,* B07310, doi:10.1029/2005JB003772.

RESULTS

Background

During the past several years, we have been investigating frictional properties of rocks at nearly seismic slip velocities. Our experiments show that two distinct weakening mechanisms occur at velocities above ~1 mm/s. One of these is a previously unknown mechanism, gel weakening, which operates above 1 mm/s and requires hundreds of mm of slip to be effective. The other mechanism, flash heating of asperity contacts, only operates above 100 mm/s (for many crustal silicate rocks) and only requires fractions of a mm of slip to be effective.

Weakening via the gel mechanism is so extreme for quartz rocks that our data extrapolate to a strength of essentially zero at a coseismic slip rate of ~1 m/s [*Di Toro et al.*, 2004]. Complete strength recovery at low or zero slip rate after rapid sliding occurs over times of 100 to 2000 s, suggesting that the gel is thixotropic. Although the formation of a silica gel layer explains our observations, further knowledge is required to better understand this mechanism and its applicability to earthquakes, including a better understanding of the roles of water and temperature. During this year we have conducted new experiments on flash heating/melting exploring the role of ambient temperature and surface roughness, since theory makes testable predictions about their effects. Results obtained during the past year have caused us to question the validity of some of our earlier conclusions that flash weakening causes all silicate rocks to slide with a low friction coefficient, ~0.2 or less, at seismic slip rates. We need to resolve the discrepancy between our earlier results and our recent ones. Due to the importance of this issue we need to confirm that flash heating is definitely the mechanism responsible for the small-displacement, highest-velocity weakening we previously observed.

Recent results and insights from high-speed friction experiments

Introduction. Our research efforts of the past year have focused on further understanding and quantifying the frictional behavior of crustal rocks at near-seismic slip rates. We have focused primarily on obtaining a better understanding of dynamic fault weakening due to flash heating of asperity contacts and further delineating the conditions for which this mechanism is expected to control fault strength. In order to study these problems in more detail, we have been using the heating stage we described in last year's report that allows us to do experiments to 350 ºC in the Instron apparatus where we do our highest slip-speed experiments. The ability to elevate the ambient temperature in our experiments allows us to investigate a number of important aspects of high-speed sliding behavior for several dynamic weakening mechanisms. For the flash heating/weakening mechanism we can determine whether shifts in the weakening velocity with increasing temperature occur as predicted by theory. For the silica gel weakening mechanism, we can evaluate the effect of water on silica gel behavior, the temperature dependence of gel strength, and the effect that elevated temperatures have on healing of the gel.

Dynamic weakening due to flash heating/melting. At seismic slip rates, high temperatures can be generated at the microscopic contacts on a fault surface, which may thermally degrade the contact strengths or melt the contacts, yielding dramatic reductions in fault strength. This 'flash weakening' mechanism is reasonably well understood theoretically, and predictions of macroscopic frictional strength due to flash heating, employing appropriate material properties for earth materials with laboratory-like contact dimensions, are in good agreement with data from some high-speed friction experiments on rocks [*Rice*, 2006a], including those from our laboratory [*Goldsby and Tullis*, 2003; *Goldsby and Tullis*, 2007; *Tullis and Goldsby*, 2003], Vikas Prakash's lab at Case Western University [*Prakash and Yuan*, 2004; *Yuan and Prakash*, 2005], and Toshi Shimamoto's lab [*Hirose*, 2002; *Hirose and Shimamoto*, 2004; *Tsutsumi and Shimamoto*, 1997]. However, several questions arise with regard to the operation of this mechanism on natural faults. Is flash weakening important at seismic slip rates for highly comminuted fault gouge, which may have contact dimensions much smaller than lab dimensions? Does flash weakening occur for gouge samples undergoing distributed shear rather than localized slip at earthquake slip rates? Do clay minerals, common fault zone constituents, undergo significant weakening due to flash heating?

Theory [*Beeler et al*., 2008; *Rice*, 1999; *Rice*, 2006] indicates that for flash weakening the weakening velocity is given by $V_w = (\pi\kappa / D)\ [\rho c\ (T_w - T_f)/\tau_c]^2$ where V_w is the weakening velocity (above which the shear resistance falls off dramatically as $1/V$, where V is the slip velocity), κ is the thermal diffusivity, D is the diameter of the asperity contacts, ρ is the density, c is the heat capacity, T_w is the temperature above which substantial weakening occurs, T_f is the average fault temperature, and τ_c is the shear strength of the contacts. One way to verify if observed weakening is due to flash heating is to vary D, since it is controlled by surface roughness. Decreasing the surface roughness, and hence D, by an order of magnitude should increase V_w by an order of magnitude, moving it from 100 mm/s to 1 m/s, out of our current range of experimental observation. Rougher surfaces should have lower weakening velocities as the equation indicates. This is because asperities will heat up to the weakening temperature before they are no longer in contact at lower velocities because they are larger and so have longer lifetimes. We tried some experiments with higher surface roughness, and found the opposite, namely there was no weakening [*Goldsby and Tullis*, 2007]. The results are shown in

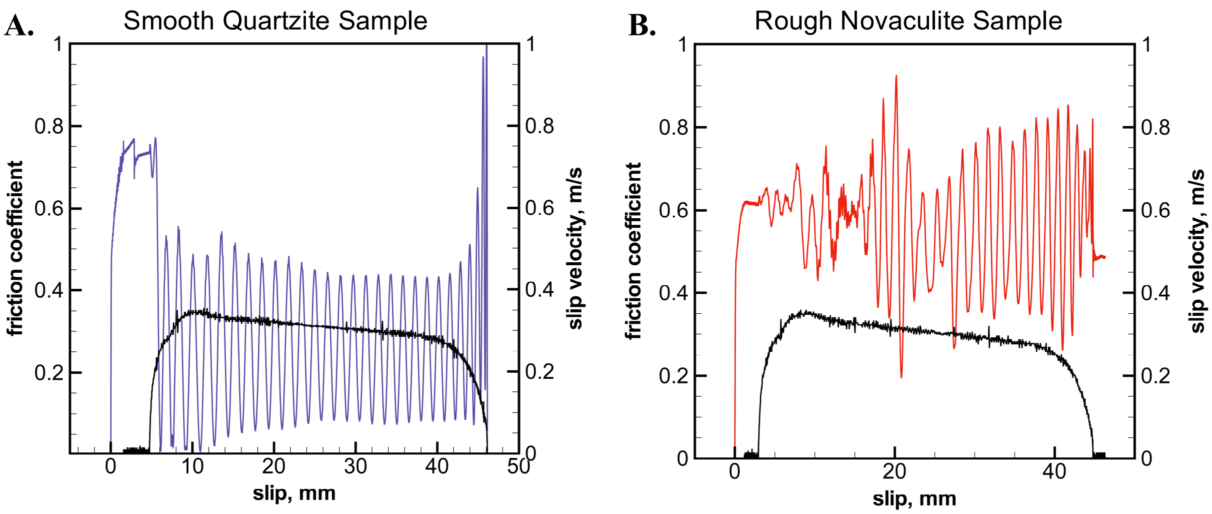

Figure 1. Comparison between behavior of two quartz rocks with different surface roughness and hardness, and consequently different thicknesses of generated gouge layers. **A)** is for a quartzite sample that is quite hard and for which the surface preparation produced a smooth surface, resulting in little gouge being produced. A micrograph of this after the experiment is shown in Figure 2A. **B)** is for a novaculite sample that is softer than the quartzite and than our typical novaculite samples and for which the surface preparation produces a rough surface, resulting in more gouge being produced than for the quartzite sample of A) and than for our typical novaculite samples.

Figure 1. Why is no weakening seen for the rougher surface whereas we expected weakening at an even lower velocity? The answer is probably related to the observation that, as is shown in Figure 2, a thicker layer of fine-grained gouge was generated in this sample that had the larger surface roughness and also used a 'softer' variety of Arkansas novaculite. Two possible explanations for the lack of any observed weakening in the presence of this layer of gouge are

A. B.

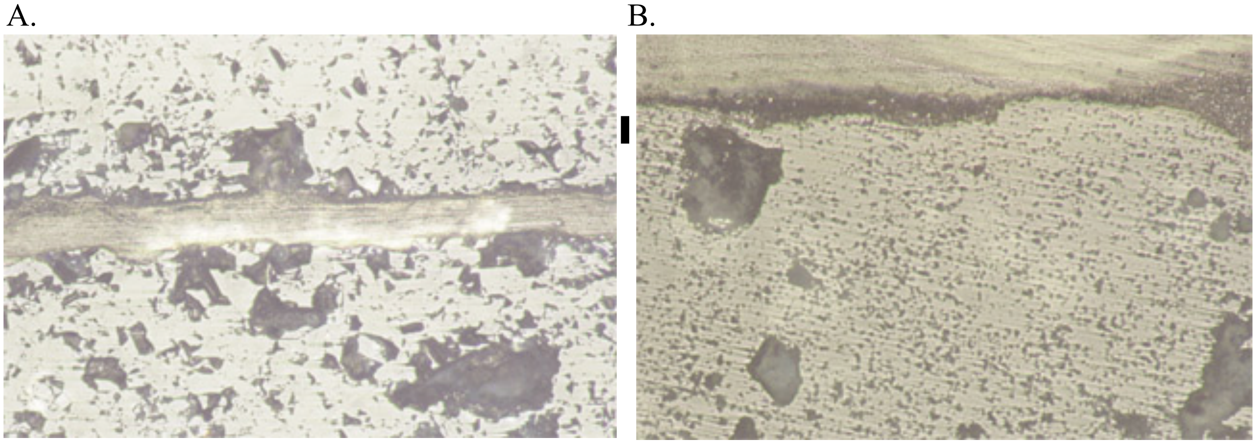

Figure 2. Reflected light optical photomicrographs at the same scale of samples corresponding to data shown in Figure 1. Vertical bar between images is 100 μm. Sections are perpendicular to sliding surfaces, parallel to slip direction. **A)** is for the hard quartzite that started with a smooth surface, and **B)** is for the soft novaculite that started with a rough surface. In A) the striated material between the forcing blocks is epoxy. Virtually no gouge coats the surfaces. In B) only the lower forcing block is shown, with epoxy at the top of the image. A dark layer of gouge 50-100 μm thick coats the lower forcing block and a similar layer probably coated the upper forcing block.

that: 1) shearing took place through a sufficient thickness of this gouge that the slip velocities on none of the slipping boundaries between particles reached V_w, and 2) that the contacts were actually between particles within the gouge of such a small size that they had small D and so did not last long enough to reach T_w.

further tests with a smaller range of surface roughness and a harder novaculite sample might allow an exploration of the effect of D as we had intended.

The other variable that might be varied to verify that our observed weakening is due to flash heating is the ambient temperature. The above equation shows that V_w increases with the square of the difference between the fixed weakening temperature and the ambient temperature. Typical values of $T_w - T_f$ are ~1000 ºC. Thus, if T_f is increased from room temperature to 300 ºC, the weakening velocity should decrease by a factor of two, an easily observable effect. It was for this reason that we constructed our high temperature sample assembly as described in our report last year.

However, we have found an unexpected result when using this high temperature assembly at room temperature – when using it on samples that are otherwise identical to samples tested in our standard room-temperature sample assembly we do not observe any weakening, in contrast to when we use our standard assembly. A comparison between the room-temperature behavior with the standard room-temperature assembly and with the high-temperature assembly is shown in Figure 3.

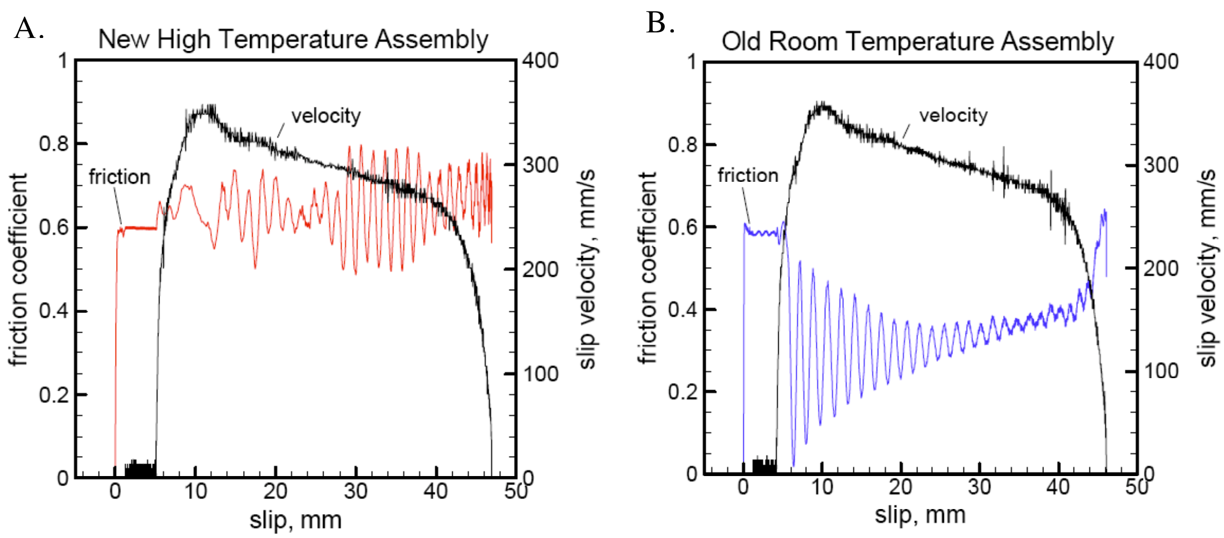

Figure 3. Results of flash heating experiments conducted in the Instron apparatus on the identical novaculite sample in the new high temperature assembly and the old room temperature assembly. Both tests conducted at a normal stress of 5 MPa.

The fact that no weakening is observed using the high temperature assembly (at either room temperature or elevated temperature) raises concerns that the weakening we have consistently observed with the standard assembly could be due to some kind of a machine artifact. Perhaps instead the weakening observed with the room temperature assembly is a valid measurement and the lack of weakening observed with the high temperature assembly is due to some artifact. It seems more likely, however, that if there is an experimental artifact it is in the results with the standard assembly.

Clearly we need to know if our apparent flash weakening measurements are real or not. Further supporting the validity of the earlier experimental data, we did find with the standard assembly that the weakening behavior differed for serpentine and there was no weakening for calcite marble, suggesting that the weakening we saw for hard silicates was not a machine artifact. However, our new results again raise concerns that the weakening observed with our standard assembly is an experimental artifact.

There are two differences between the old and the high-temperature assemblies that might be responsible for the different results. The new assembly has a higher mass, affecting both the moment of inertia and the axial inertia, and it has lower stiffness in both torsion and compression. It is possible that the stiffer older assembly might be more likely to partially loose contact or have a lower normal stress during the high speed sliding, and the oscillations we observe (e.g. Figure 3b) in many of the old friction records could somehow result from this. The normal stress and normal displacement is measured somewhat remotely and so inertial forces involving axial and rotary accelerations of the intervening masses might mean that the measured displacements and stresses might not represent those at the sliding interface of the rock. Alternatively, there is a possibility that in the new assembly with its higher moment of inertia, actual weakening might not be detected, although this seems unlikely to us. Some previous analysis we undertook of this possible problem suggested the errors would not be large, but our new results with the different sample assembly has caused us to question whether we understand the machine behavior as well as we thought.

Regardless of the origin of the discrepancy between the results with the two assemblies, it is extremely important that we resolve the matter – is the weakening measured with the old assembly the correct result or is the lack of weakening with the high-temperature assembly correct? The flash weakening mechanism is being used by theoreticians to model stress drops during simulated earthquakes and we need to know if the experimental data support the theory or not. We are working on resolving this problem.

Geophysical implications

All of the weakening mechanisms that we are studying have profound implications for the magnitude of stress-drops during earthquakes and consequently for the magnitude of strong ground shaking. The manner in which fault strength varies with displacement and rupture velocity, as well as the rate at which healing occurs as slip velocity drops behind the rupture tip, can control the mode of rupture propagation, i.e. as a crack or as a pulse. Furthermore, these data can be important for resolving questions concerning stress levels in the crust. If coseismic friction is low, and seismic data seem to constrain the magnitude of dynamic stress drops to modest values, then the tectonic stress levels must also be modest. We may have a strong crust that is nevertheless able to deform by faulting under modest tectonic stresses if the strength is overcome at earthquake nucleation sites by local stress concentrations and at other places along the fault by dynamic stress concentrations at the rupture front. Thus, understanding high speed friction is important not only for practical matters related to predicting strong ground motions and resulting damage, but also for answering major scientific questions receiving considerable attention and funding, e.g. the strength of the San Andreas fault / the heat-flow paradox, the question that ultimately is responsible for the SAFOD project.

Summary

Our experiments show that substantial reductions in shear stress can occur at slip rates faster than those usually attained in laboratory experiments, even at rates slower than typical of earthquakes and even without wholesale frictional melting. One weakening mechanism involves the formation of a thin layer of lubricating silica gel. We have found that for this mechanism to operate it in necessary that the thickness of the lubricating layer of thixotropic silica gel be greater than the surface roughness so that shearing can occur in the layer without interlocking of the surfaces. On the other hand, the weakening that we have attributed to flash weakening does not occur when a layer if gouge is present, perhaps because either slip occurs at several levels in the gouge and the weakening velocity is not reached at any location, or because the particle sizes and thus contact dimensions are so small that their weakening velocity is beyond the range of our applied velocity. Recent results with a high-temperature sample assembly do not show the weakening we have attributed to the flash weakening mechanism, unlike what we have observed previously, causing us to begin an investigation of which assembly is giving correct results. Whether either the gel or the flash weakening mechanisms is important for earthquakes is still unclear, but they are certainly plausible candidates. If the large reductions in shear stress seen in our experiments are characteristic of earthquakes, it implies that dynamic stress drops may be nearly complete and that, unless the initial stress is also small, accelerations and strong ground motions should be quite large.

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Tele: (401) 863-3829, FAX: (401) 863-2058, Email: Terry_Tullis@brown.edu
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NON-TECHNICAL ABSTRACT

Our continued experiments have shown that frictional sliding of rocks at slip speeds approaching those of earthquakes makes them much weaker than in slower conventional experiments. We have been studying two weakening mechanisms, production of a lubricating layer of silica gel on the sliding surface and generation of high temperatures at sliding contact junctions due to frictional heating. We are investigating whether any of the observations could be due to an experimental artifact. If weakening also occurs during earthquakes, stress reduction during earthquakes could be so large that the size of damaging ground motions might be larger than usually expected.